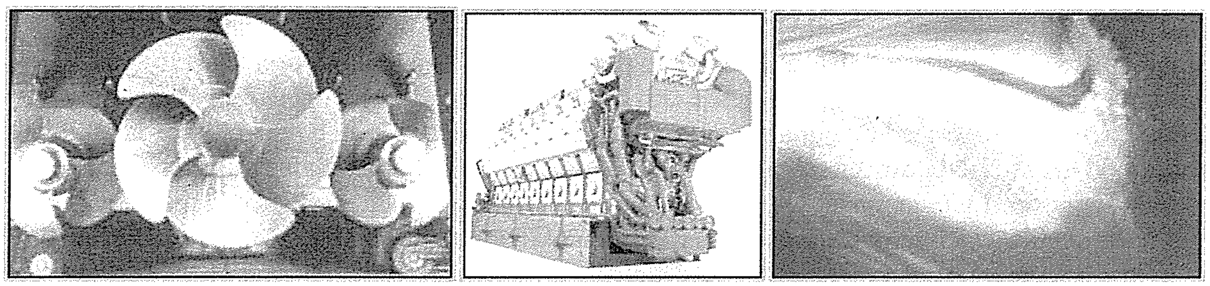
LNG shipping via fleet of LNG carriers

LNG carriers are traditionally powered by steam turbines burning marine diesel or heavy fuel oil. The new generation of LNG carriers are increasingly installing diesel-electric propulsion systems in which two to four large engines generate electricity that power electric drives. Dual-fueled engines, such as those made by Wärtsilä that CMS has based its propulsion and emissions estimates upon, can burn either marine diesel/heavy fuel oil and/or natural gas — the source of which is the boil-off gas from the cargo. Emissions from this segment of the LNG supply chain are the result of converting propulsion fuel into carbon dioxide (plus some methane).

CMS based its fuel consumption estimates on statements in the CSLC (2006) *Revised Draft EIR*. Although BHP has "not finalized design specifications for LNG carriers" or determined (to our knowledge) the size, propulsion type, or fuel preference, CMS used the lower end of the vessel size (138,000 m^3) cited, modeled emissions and fuel consumption for three scenarios (low, medium, and high), and derived total annual trips based upon the same basic criterion followed throughout this exercise: the delivery of 800 million cubic feet of gas daily (292 Bcf/yr) to southern California markets.[17]



Propellers, 50DF dual-fueled engine, and a bulbous bow plowing through pacific waters. www.wartsila.com

The BHP permit application cites a power rating of 60,000 HP (44.7 MW), and while this is higher than the propulsion rating of other ships of similar size,[18] CMS has used the BHP-supplied data for the calculations.[19] Furthermore, CMS assumed the use of Wärtsilä 50DF duel-fuel engines as power plants, with CO_2 emission rates of 430 to 630 grams of CO_2 per kWh, depending on fuel type.

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[17] CSLC (2006) *Rev Draft EIR*, p. 2-21: "LNG carriers would have a capacity ranging from 36.5 to 55.5 million gallons (138,000 to 210,000 m^3). Of this volume, an estimated 4 million gallons (15,100 m^3) would be consumed by the carrier while in transit for fuel and for maintaining the cold tanks; the remaining 32.5 or 51.5 million gallons (123,000 or 195,000 m^3) would be transferred to the FSRU. LNG carriers would be powered by natural boil-off gas from their LNG cargo, as agreed with the U.S. Environmental Protection Agency (USEPA) (Klimczak 2005). The Applicant has not finalized design specifications for LNG carriers; therefore, the diesel storage capacity for LNG carriers cannot be estimated at this time."

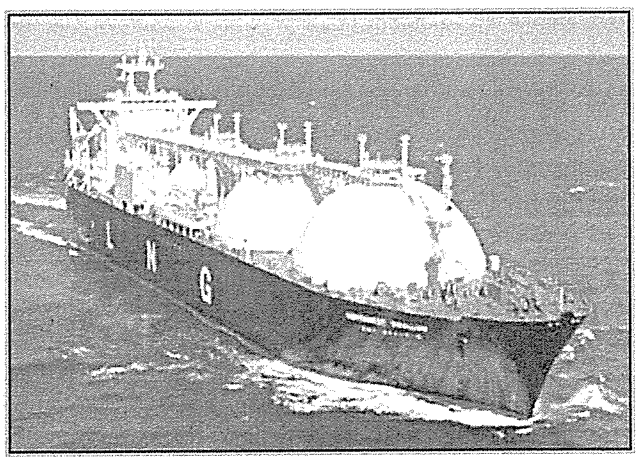
[18] Küver et al (2002) "Evaluation of Propulsion Options for LNG Carriers," show the predicted power requirement — albeit for propulsion only — of a state-of-the-art LNG carrier of 145,000 m^3 size cruising at 19.5 knots (as we assume here) as ~25 MW, not the 44.74 MW used by BHP. Küver also models the boil-off rate (0.15% BOG/d) vs fuel requirement for a 142,000 m^3 carrier, which consumes its full boil-off rate of 100 tonnes/day at 19.5 knots, thus requiring no re-liquefaction and no supplementary diesel fuel consumption.

[19] Either BHP is including high auxiliary power requirements — for other ship functions, hotel loads, and possibly powering re-liquefaction compressors so as to deliver the maximum cargo to Cabrillo as opposed to using the boil-off gas as engine fuel — or BHP will reduce the expected ships' power rating, or increase the vessel size. Resolving this conflicting information may justify a re-calculation of the fuel type and quantity for the LNG trade route. Note: If BHP was planning to use the next-generation carrier size (up to 250,000 m^3), its fleet would to make fewer than the stated ~"2.5 deliveries per week" (BHP, p. 3-5).

Assuming Scarborough/Pilbara as the origination of the gas and LNG, CMS estimates a trade route of 9,100 miles, or 7,908 nautical miles, each way. LNG carriers recently delivered from shipyards typically achieve 19.5 knots (though this will vary by trade route).[20] means a voyage of 406 hours, or almost 17 days en route. CMS modeled three fuel scenarios as follows:

1. Gas-only mode that used LNG boil-off gas plus an additional quantity of vaporized natural gas sufficient to fuel the engines: 430 gCO_2/kWh times 18.1 million kWh for each one-way trip = 7,800 tonnes of CO_2, consuming 6,740 m^3 of LNG en route;
2. Duel-fuel mode that burned boil-off gas at the normal rate supplemented with diesel fuel at 630 gCO_2/kWh, which means a blended rate of 529 $gCO_2/kWh \Rightarrow$ 9,590 tonnes of CO_2 and the consumption of 3,420 m^3 of LNG en route (of which the boil-off gas, at 0.15 percent per day, would supply approximately 54 percent of the required fuel);[21]
3. Diesel-only mode at 630 gCO_2/kWh resulting in 11,430 tonnes of CO_2 for each one-way trip, with zero LNG consumption. Note: this assumes re-liquefaction of the boil-off gas,[22] which requires on-board compressors and a power requirement of up to 3.5 MW (Roger Courtay, quoted in *Naval Architect*, Nov03). Ship design aside, BHP's blue-water fuel option will most likely be driven by fuel costs versus the value of the additional deliverable cargo, not emissions.[23]

These three options become the "low," "medium," and "high" emissions scenarios. Annual low emissions totals 1.80 million tonnes of CO_2-eq ($MtCO_2$-eq), with 112 loads of LNG delivered (2.2 berthings per week). The medium estimate totals 2.09 $MtCO_2$-eq, and 107 berthings per year. The high emissions estimated totals 2.37 $MtCO_2$-eq, with 101 berthings per year. CMS based its gas production estimate at Scarborough plus the Pilbara liquefaction capacity on the gas-only propulsion fuel mode cited in the CSLC *Draft EIR* (p. 2-21, quoted above) and its reference to consuming a large quantity of LNG boil-off gas en route. The quantity of natural gas consumed for the LNG carrier operations totals 32 Bcf per annum, which is equivalent to 0.69 million tonnes of LNG per year. (See Table 2 above and the attached worksheet Tables 1, 7, 8 and 9 for details, calculations, assumptions, documentation, and results.)



An LNG carrier with Moss spherical tanks shown in BHP literature.

[20] Colton, Maritime Business Strategies (2006), www.coltoncompany.com

[21] As noted in footnotes on the previous page, BHP is probably in error in citing a 60,000 HP vessel. Küver et al (2002) show that a 142,000 m^3 carrier with diesel-electric propulsion will theoretically consume its BOG at 19.5 knots (albeit, for propulsion only). CMS estimates may be revised with updated or more complete BHP data.

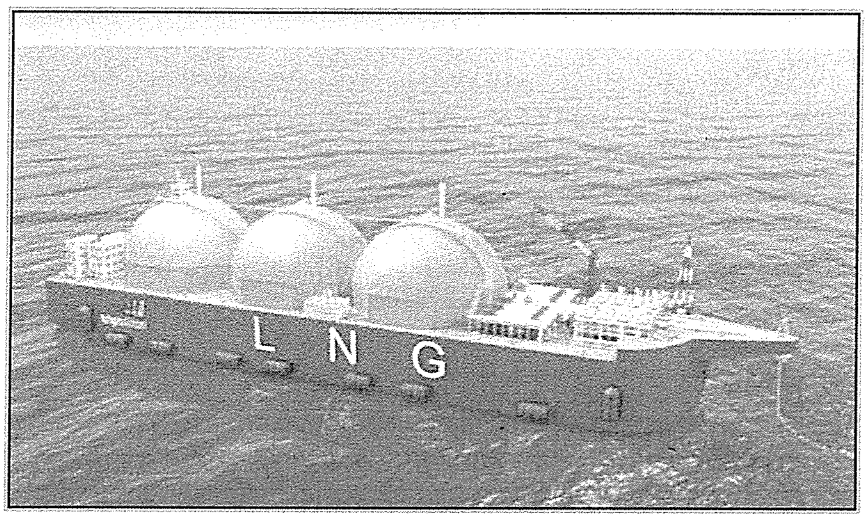
[22] In the high emissions scenario the LNG is reliquefied onboard in order to maximize the amount of LNG delivered. See Lunde (2005). Hamworthy is a leading proponent and systems vendor for this concept. www.hamworthy.com

[23] BHP has stated that its LNG carriers will burn only natural gas while in Federal waters. CLSC *Revised Draft EIR*, pp. 4.6-15, 16, 34, states that the LNG tankers will run "primarily on natural gas" within 25 miles of shore.

LNG terminal: Cabrillo Deepwater Port

Next, CMS used BHP-supplied data on the amount of natural gas needed to operate the Cabrillo Deepwater Port, including gas used to generate electricity on board the LNG carriers that power pumps to transfer 57,000 to 63,000 tons of LNG from the carrier to the FSRU (at a design rate of 65,000 gallons per minute). CMS also included fuel consumption for tenders, tugs, and crew boats, and natural gas burned in the four (of eight) constantly operating 115 million Btu/hr vaporization units on the FSRU.[24] Electricity also has to be generated to run the FSRU's cranes and booms, waste transfer pumps, water pumps as well as hotel loads such as water heating, ventilation, cooking (for a crew of 30 to 50 persons), lighting, and electronic equipment. Other emissions sources include methane from incomplete combustion of fuel.

The generating capacity onboard the FSRU totals 25 MW and is to be provided by four Wärtsilä 9L50DF duel-fuel generators.[25] BHP's own emissions estimate from the sources listed above totals 0.26 million tonnes CO_2-equivalent per annum (including 39 tonnes of methane). BHP also estimated Start-Up emissions for the break-in phase of the Cabrillo Port totaling 0.01 milllion tonnes of CO_2-eq.



Sketch of the Cabrillo Deepwater Port Floating Storage and Regasification Unit (FSRU). Source: BHP.

CMS adopts BHP's emissions estimate as the "low" estimate. The CMS "high" estimate totals 0.43 $MtCO_2$-eq for the annual operating emissions (plus 0.02 $MtCO_2$-eq for Start-Up) by adding fugitive methane from the FSRU operations (note: BHP estimated methane from incomplete combustion but did not estimate fugitive methane; CMS applies BHP's cited methane rate [0.39 gCH_4/HP-hr] to BHP's trans-Pacific LNG carrier trade route). Since there is growing pressure on operators and engineers to reduce both flaring and venting at FPSOs and FSRUs, CMS lowers the benchmark methane emission rate by applying one-half of the average U.S. gas industry

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[24] This is an impressively large operation. The FSRU is 970 feet long and covers about four acres (see image above). The LNG re-gasification units have a combined heat rate of 460 million Btu/hr — sufficient capacity to heat the homes in a mid-sized mountain town in winter — in order to heat and vaporize ~800 tons/hour of the cryogenic liquid from -259°F to 41°F.

[25] Three Wärtsilä gen-sets of 8.3 MW plus one back-up generator; each will typically be fueled with natural gas but capable of running on diesel whenever required, e.g., in emergency natural gas curtailment situations. BHP (2005), section 2.2.

leakage rate for gas processing facilities. Presumably, BHP's FSRU will achieve a lower rate than typical gas processing facilities, but BHP supplies no estimates of its own and CMS does not have access to measured data from such facilities. CMS applies a reasonable estimate in lieu of BHP- or CSLC-published estimates.[26]

In addition, CMS estimates that the six-month FSRU construction phase will consume ~1.1 million gallons of diesel and marine diesel fuel and emit 0.01 $MtCO_2$-eq for pipelaying and related construction activities. This involves a flotilla of pipe-laying vessels and barges and tenders and crew boats for the construction of the twin 24-inch subsea natural gas pipelines connecting the FSRU to onshore gas networks, as well as an armada of trucks and trenchers and dozers and backhoes for the pipelines' shore crossing and utility-connections. Construction emissions are added to Cabrillo's Start-Up phase, and both the "low" and "high" emissions estimates for Start-Up are added to Cabrillo's operational emissions by annualizing Start-Up over a 25-year period.[27]

Anchor handling tug *Primus* of Antigua, left, and pipelaying vessel *Solitaire* of Panama, right.
Source: Maritimephoto.com, with permission.

Ultimate consumption of the gas delivered to California customers

The largest component of the supply chain emissions is, not surprisingly, the combustion of the natural gas delivered to SoCalGas and distributed to the utility's customers. While a common benchmark is to estimate carbon dioxide from complete combustion of the natural gas delivered, CMS makes two adjustments. First, we deduct small amounts of gas diverted to other, non-fuel uses, and are consequently sequestered into other products rather than combusted to CO_2 and emitted to the atmosphere; secondly, we deduct a small fraction to account for the small

[26] BHP has estimated emissions of methane from incomplete combustion of natural gas used in the equipment categories listed in Table 10 of the attached worksheets. The BHP estimate, as far as we can ascertain, does not include fugitive emissions of methane from leaky pipes, valves, flanges, tanks, seals, and other fuel containment systems. CMS has not evaluated the legal requirement to estimate additional methane emissions, nor can CMS make an engineering estimate of such emissions. CMS does attribute one-half of the emissions rate from natural gas processing (0.5 * 28.22 tonnes CH_4/Bcf) plus one-tenth of methane emissions from gas distribution and storage (0.1 * 105.73 tonnes CH_4/Bcf) as an indicator that a Cabrillo-specific emissions estimate must be made. These rates are applied to total natural gas throughput (292 Bcf delivered to SoCalGas plus 5 Bcf required for Cabrillo operations).

[27] While a 25-year time horizon may be shorter than total anticipated project lifetime (40 years is mentioned in the CLSC *Draft EIR*), it is close to the 21.1-year life-expectancy of Scarborough gas field, assuming that the identified 8.0 trillion cubic feet of reserves are produced at an annual rate of 379 Bcf/yr detailed Table 2 above. This annual production rate accounts for the gas delivered to SoCalGas by BHP as well as the gas consumed at the Scarborough gas platform, in the 270-km subsea pipeline to the Pilbara LNG plant, for liquefaction and LNG plant use, gas consumption by LNG carriers, and gas requirements of the Cabrillo FSRU. Without these adjustments, the 800 million cf of gas per day deliverable to SoCalGas equals 292 Bcf/yr, or a simple 27-yr depletion schedule.

proportion of the fuel that is not combusted into CO_2. The first calculation is based on U.S. non-fuel uses of natural gas, although southern California's end-use gas consumption patterns likely differ somewhat from the nation as a whole, whereas the second is based on default values used by the U.S. EPA and the IPCC inventory protocols.

Non-fuel uses of natural gas are chiefly for fertilizer and methanol production and averages about three percent of total U.S. natural gas consumption. An analysis by CMS shows that the actual sequestration rate must also account for the proportion of non-fuel uses that is relatively quickly returned to the atmosphere as greenhouse gases; methanol, for example, is used in transportation, and fertilizer production emits both nitrous oxide and CO_2. Once adjusted, the sequestration rate is reduced from 3.05 to 0.3 percent of total natural gas consumption.

According to EPA and IPCC inventory guidelines, 0.5 percent of natural gas in the combustion stream is not combusted to CO_2. Finally, a methane leakage rate is applied to gas distribution based on typical leakage rates in the natural gas industry. See the worksheet Table 12 for details.

The "low" and "high" estimates are numerically close, given the small variability applied to combustion emissions minus "sequestered non-fuel uses" and "non-combusted" fractions. The emissions estimates range from 15.82 to 15.89 $MtCO_2$ plus 0.58 to 0.72 $MtCO_2$-eq of methane for an average total "gas distribution and combustion" estimate of 16.50 $MtCO_2$-eq per year.

Cyclone Glenda satellite image hours after it pummeled Onslow, Western Australia (site of BHP's proposed Pilbara LNG plant) with 176-mph winds on 30Mar06, left; bulk carrier *Graham* facing a cyclone at sea, 2002, right.

Summary

A full accounting of emissions of greenhouse gases arising from the supply chain linked to BHP Billiton's proposed LNG receiving terminal has been presented. Contrary to BHP's submitted emissions estimates — which included only emissions from the Cabrillo Deepwater Port operations — CMS has included emissions from the natural gas production platform offshore Western Australia, transportation by subsea pipeline to the emissions-intensive onshore liquefaction plant, followed by shipping in a fleet of LNG carriers across 7,900 nautical miles of Pacific Ocean, receiving and regasification at the Cabrilllo terminal 14 miles offshore Ventura and Los Angeles Counties, and finally combusted by gas customers in southern California. All of these steps are required to deliver the quantity of natural gas premised in the BHP *Construction Permit Application* filed with Federal agencies and the State of California Lands Commission.

Table 3: Supply Chain emissions: low estimate

Supply-chain segment	Methane	Carbon Dioxide	Total	Percent
	thousand tonnes of CO_2-eq			
Gas production (Scarborough)	254	400	654	3.1%
Gas pipeline to Pilbara LNG	90	211	301	1.4%
Liquefaction plant at Onslow	110	1,855	1,965	9.2%
LNG carrier fleet, Australia → California	44	1,755	1,799	8.4%
Cabrillo Deepwater Port Operations	0.9	261	261	1.2%
Cabrillo Start-Up (annualized, 25yrs)	negl	0.4	0.4	0.0%
Ultimate gas distribution & combustion	578	15,815	16,393	76.7%
Total supply-chain GHG emissions	1,078	20,300	21,378	100.0%
Percent	5.0%	95.0%	100.0	

Table 4: Supply Chain emissions: high estimate

Supply-chain segment	Methane	Carbon Dioxide	Total	Percent
	thousand tonnes of CO_2-eq			
Gas production (Scarborough)	339	589	928	3.8%
Gas pipeline to Pilbara LNG	181	317	497	2.1%
Liquefaction plant at Onslow	239	3,169	3,409	14.1%
LNG carrier fleet, Australia → California	49	2,320	2,369	9.8%
Cabrillo Deepwater Port Operations	169	261	431	1.8%
Cabrillo Start-Up (annualized, 25yrs)	negl	0.4	0.5	0.0%
Ultimate gas distribution & combustion	722	15,888	16,610	68.5%
Total supply-chain GHG emissions	1,699	22,548	24,248	100.0%
Percent	7.0%	93.0%	100.0	

Note: BHP Billiton's estimate of annual emissions at Cabrillo totals 261 thousand tonnes CO_2-eq.
Note: Tables 3 and 4 are in metric tonnes (1 tonne = 1.1023 short tons).

Conclusions

The supply chain emissions analysis summarized in this report provides a superior measure of the proposed Cabrillo Deepwater Port's impact on the global climate. No energy supply project of the scale proposed by BHP Billiton is without substantial emissions of greenhouse gases in every critical link of the supply chain.

There is no satisfactory rationale for ignoring emissions arising from the proposed supply chain — without which the project is infeasible — in an environmental impact report.

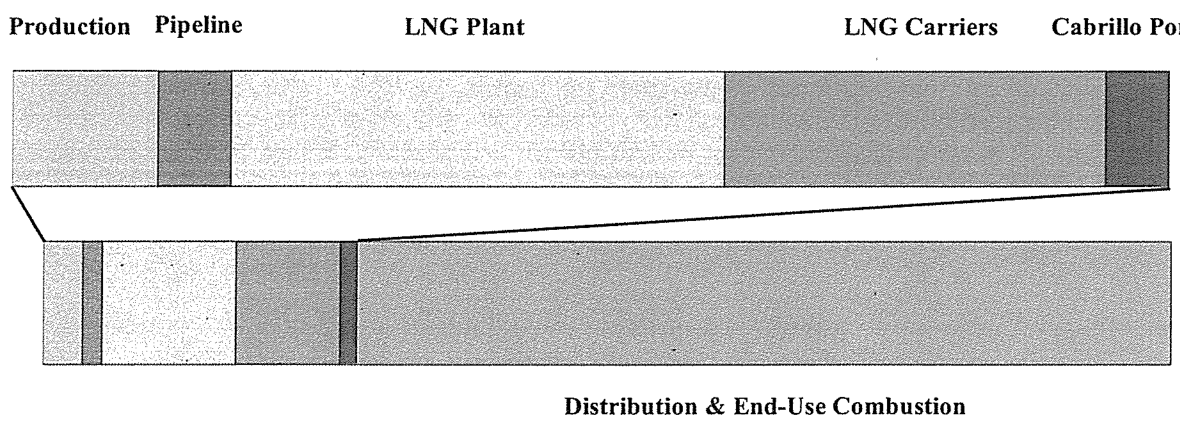
The accuracy of CMS's estimates can be improved with contributions and data-sharing by both the proponent and the State of California Lands Commission. CMS uses conservative estimation procedures, performance benchmarks, and emissions factors, and each step of the calculations is fully documented and transparent. Considerable uncertainties are unavoidable in an analysis with so many unknowns. BHP's documentation of the planned supply chain is sparse, and BHP only estimated emissions the Cabrillo Deepwater Port segment.

Moreover, technological change is rapid in the fast-growing LNG sector: operators are under pressure to market stranded natural gas from offshore fields. Also, public and regulatory pressures increasingly mandate emissions mitigation measures, especially regarding the transport, storage, and processing of LNG. The private sector can profit handsomely from increasing efficiency and trading emissions. Finally, the Cabrillo Port and its requisite supply segments will not be completed until 2011 or later. All of these factors suggest considerable evolution of the technologies deployed along the entire supply chain. Given these uncertainties, the CMS estimates of emissions from the BHP supply chain must be regarded as preliminary and subject to improvement with access to better engineering data as the project matures.

The BHP estimate, echoed by California State Land Commission's *Revised Draft Environmental Impact Report*, concludes that the project's emissions of greenhouse gases are "insignificant" and "represent less than 0.06 percent of the ... emissions produced in California in 2002."[28]

CMS results show a different picture, with the supply chain emissions from production through end-use of the delivered natural gas equal to 4.3 to 4.9 percent of California's total GHG emissions, and 5.3 to 5.9 percent of CO_2 emissions using Energy Information Administration state emissions data.[29] Broadening the comparison — again accounting for emissions from production in Australia to combustion of the gas delivered to end-use customers in California — shows that emissions from BHP's proposed LNG project are equivalent to 0.30 to 0.34 percent of total U.S. emissions (using EIA data for 2004). BHP's estimated emissions from its operation of the Cabrillo Deepwater Port comprises a mere 1.5 percent of emissions from the entire supply chain. This relationship is shown in Figure 2, with the Cabrillo emissions in red.

Figure 2. Bars showing relative emissions contributed by each supply chain segment



[28] CSLC, p. 4-20: "Project operations would cause annual CO_2 emissions of 0.29 million tons per year (MMtons/yr). Project start-up and construction activities would result in one-time CO_2 emissions of 0.010 MMtons and 0.017 MMtons, respectively. These emissions represent less than 0.06 percent of the 543 MMtons of CO_2-equivalent greenhouse gas emissions produced in California in 2002 (CEC 2005). The greenhouse gas emissions from the Project would be insignificant alone, but could exacerbate, in combination of existing greenhouse gases, global warming effects."

[29] Using the cited CEC emissions data for all greenhouse gases in 2002. Supply chain CO_2 emissions comprise 5.27 to 5.84 percent of California's CO_2 emissions in 2001 (EIA data).

Another notable result of the CMS study is that the supply chain adds 35 to 53 percent to the common way of measuring emissions from natural gas consumption, namely the combustion of the gas itself, disregarding the supply chain emissions. This is the LNG supply chain "adder," although it must be emphasized that we have not estimated ancillary emissions from other natural gas supply alternatives — such as the Long Beach or Baja Mexico LNG proposals, sources of domestic gas by pipeline from Texas or Colorado, or, for that matter, coal-fired electric generation, renewable electricity options, or end-use efficiency of any and all uses of natural gas in California.[30]

Consequently, the results presented in this report do not argue for or against the proposed LNG project. Instead, the objective has simply been to fill the analytical gap left by BHP Billiton's and CSLC's omission of estimating the emissions from the remainder of the required natural gas supply chain.

[30] See, for example, Hunt et al (2006), Lovins et al (2004), and Lovins et al (forthcoming late 2006).

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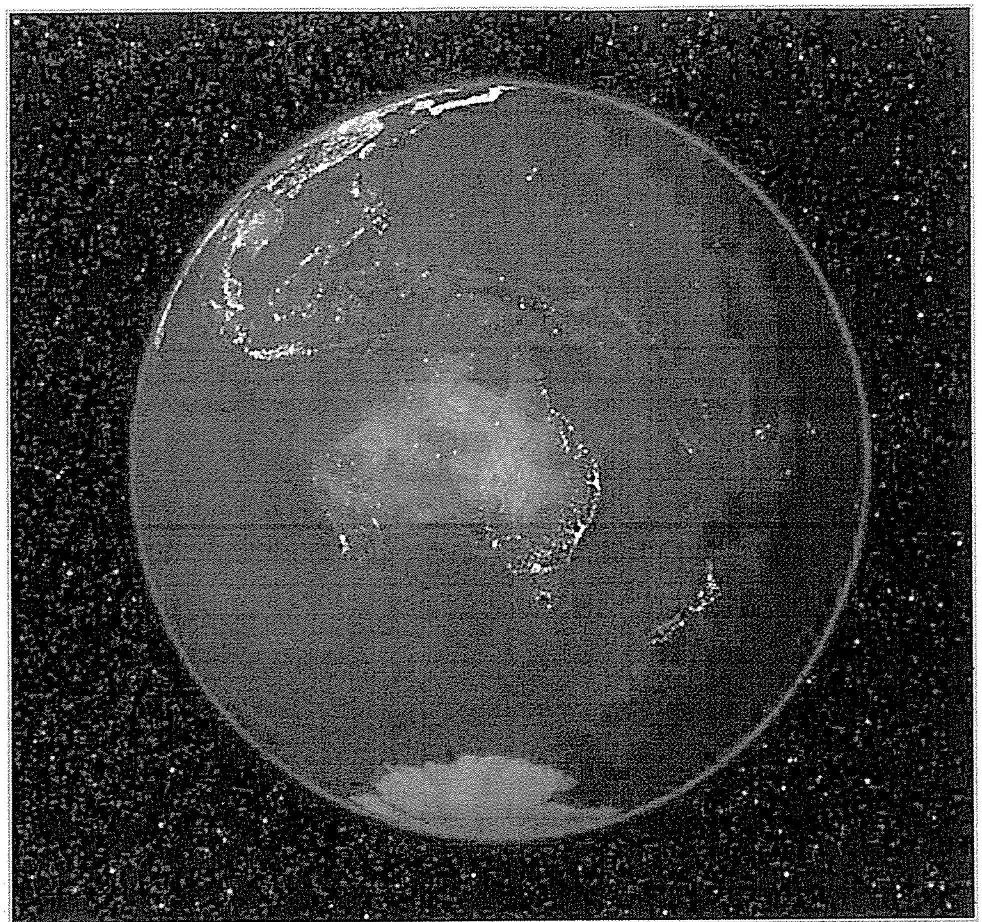
Conversions[31]

Table of conversions		
1 tonne LNG	46,467	cubic feet gas
1 cubic meter LNG	21,189	cubic feet gas
1 cubic meter LNG	0.4560	tonne LNG
1 tonne LNG	2.1930	cubic meter LNG
1 tonne LNG	51.1138	million Btu
1 cubic meter LNG	23.3079	million Btu
1 million cubic feet gas	21.5206	tonnes LNG
1 million cubic feet gas	47.1943	cubic m LNG
1 nautical mile	1.1508	statute miles
1 horsepower (HP)	0.7457	kW
1 kW	1.3410	horsepower (HP)
1 million cf gas per day	7,885	tonnes LNG per yr
1 tonne	1.1023	short (US) tons
1 kg	2.2046	lb
1 cubic meter	35.3147	cubic feet
Combustion of 1 Bcf	54,602	tonnes CO2
1 tonne CO2	18,314	cubic feet gas
Combustion of 1 m^3 LNG	1.1570	tonnes CO2
Combustion of 1 tonne LNG	2.5372	tonnes CO2

[31] Conversion sources: U.S. Dept of Energy (2005) *Liquefied Natural Gas: Understanding the Basic Facts*, p. 9; miscellaneous engineering sources; and calculations by CMS.



A portion of the LNG trade route from NW Australia to southern California, around the edge of Earth's disk at ~2 o'clock.

Notes